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Groundwater Potential Analysis of Adamawa State Northeastern Nigeria Using Geospatial and Multi-Criteria Decision Analysis Techniques

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ABSTRACT
Groundwater remains one of the most dependable sources of freshwater for domestic, agricultural, and industrial purposes, particularly in regions experiencing increasing population growth and seasonal variability in surface water availability. This study assessed the groundwater potential of Adamawa state using geospatial and Multi-Criteria Decision Analysis techniques. Rainfall data was obtained from Nigerian Meteorological Agency, satellite images and Digital Elevation Model was acquired from the United States Geological Survey. Thematic maps were produced for factors such as geology, rainfall, drainage density, soil, lineament density, slope, and land use/land cover. The weighted overlay analysis technique was employed to generate the groundwater potential map which was validated with existing borehole yields. Pairwise comparison of the groundwater influencing factors revealed that geology had the highest degree of influence on groundwater occurrence with a weighted level of significance of 24.6%, followed by rainfall (20.8%) and drainage density (17.0%). Soil, lineament density, slope, and land use/land cover contributed 13.7%, 11.2%, 8.4%, and 4.4% respectively. The generated groundwater potential map was reclassified into five zones: very low, low, moderate, high, and very high groundwater potential zones. The results showed that areas of very high groundwater potential are predominantly concentrated within the central region and parts of the southern region of the state with very low groundwater potential zones occupied 1,058.84 km² (2.96%), low potential zones covered 13,332.71 km² (37.32%), moderate potential zones occupied 8,153.76 km² (22.83%), high potential zones covered 11,364.66 km² (31.82%), while very high potential zones accounted for 1,811 km² (5.07%) of the total areal coverage. Overall, areas with moderate to very high groundwater potential constitute approximately 59.78% of the total areal coverage, indicating that a significant areal coverage of the state is suitable for groundwater development. The finding also revealed that 78.20% of existing boreholes fall within zones corresponding to their actual yields, together with a Pearson correlation coefficient (R = 0.782), provides compelling evidence that the groundwater potential mapping approach used in this study is reasonably reliable.

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Keywords: Zoned GWP Map, Thematic factors, Geospatial Technique, AHP, Spatial Analysis and Adamawa State

INTRODUCTION

Groundwater is one of the most important natural resources for domestic, agricultural, and industrial development, particularly in developing countries where access to reliable surface water is limited (Aranguren-Díaz et al., 2024; Jac, 2021). In many parts of sub-Saharan Africa, groundwater serves as a major source of potable water because of its relative availability, better quality, and resilience to seasonal climatic variations (Eludoyin and Olanrewaju, 2022; Danert and Healy, 2021). Nigeria, with its rapidly growing population and increasing urbanization, depends heavily on groundwater resources to meet water demands for rural and urban communities (Igimoh et al., 2026; Irene et al., 2025). However, the uneven spatial distribution of groundwater resources, climate variability, and increasing anthropogenic pressure have intensified the need for sustainable groundwater exploration and management strategies (Oniku et al., 2025)

Adamawa state is characterized by semi-arid to sub-humid climatic conditions, variable geological formations, and seasonal rainfall patterns that strongly influence groundwater recharge and occurrence (Joshua et al., 2023). Communities within the state increasingly depend on groundwater due to inadequate surface water supply, recurrent drought conditions, and population growth. Despite the importance of groundwater in the area, borehole failures and inconsistent groundwater yields remain major challenges, largely due to insufficient hydrogeological information and poor groundwater prospecting techniques. Consequently, there is a growing need for reliable and cost-effective methods for identifying GWP zones within the state which is a major part of the Upper Benue River Basin, Northeastern Nigeria (Mbah and Nur, 2022)

Conventional groundwater exploration methods, such as extensive geophysical surveys and exploratory drilling, are often expensive, time-consuming, and spatially limited (Odoh et al., 2024). Recent advances in Geographic Information Systems (GIS), Remote Sensing (RS), and Multi-Criteria Decision Analysis (MCDA) techniques have provided efficient alternatives for groundwater potential assessment.

These techniques enable the integration of various hydrogeological and environmental factors that control groundwater occurrence, including geology, slope, drainage density, lineament density, rainfall, land use/land cover, soil characteristics, geomorphology, amongst others (Amos-Uhegbu et al., 2024; Singh et al., 2026; Alrawi et al., 2022). The integration of these thematic layers within a GIS environment facilitates spatial analysis and the delineation of GWP zones with improved accuracy and reduced cost.

Amongst some MCDA techniques used for the purpose of GWP delineation, the Analytical Hierarchy Process (AHP) has become widely applied in GWP mapping because it allows the weighting and ranking of influencing factors based on their relative importance (Echogdali et al., 2022). The AHP approach reduces subjectivity in decision-making and supports the generation of scientifically reliable GWP maps. Recent studies have demonstrated the effectiveness of integrating Geographic Information System (GIS), Remote Sensing (RS), and AHP techniques in groundwater exploration across different geological environments. For instance, Amos-Uhegbu et al. (2024) applied GIS and MCDA techniques in the Lower Benue and Niger Delta Basins of Nigeria and identified geology, rainfall, and slope as major determinants of groundwater occurrence. Similarly, Ejepu (2020) used GIS-based MCDA techniques in the Upper Niger River Basin Development Authority area and successfully delineated GWP zones using thematic layers such as geology, drainage density, and lineament density. Several recent studies have also highlighted the growing importance of geospatial techniques in groundwater assessment within semi-arid regions. Saidu et al. (2024) integrated GIS and AHP techniques for GWP mapping in Northern Nigeria and emphasized the suitability of geospatial approaches for groundwater management in water-scarce environments. Likewise, Shinggu et al. (2025) assessed GWP in Mubi South Local Government Area of Adamawa State using remote sensing and GIS approaches, demonstrating the effectiveness of geospatial analysis for sustainable urban water resources management. In Edo State, South-south Nigeria, researchers adopted a triangulation approach involving geospatial technology and MCDA to evaluate GWP and reported that lithological and structural characteristics significantly influence groundwater distribution.

Despite increasing applications of GIS and multi-criteria decision analysis (MCDA) in groundwater studies, important hydrogeological uncertainties remain unresolved in Adamawa State. Groundwater occurrence is controlled by complex interactions among lithology, weathering depth, fractures and lineaments, topography, drainage, soil, rainfall, and land use. However, the relative importance of these controls may vary considerably across Adamawa's diverse geological and physiographic environments. Consequently, groundwater potential maps derived from a limited number of surface indicators may not fully represent subsurface aquifer productivity or spatial variability. Recent reviews emphasize that uncertainty is further increased when groundwater potential maps are insufficiently validated with borehole yield, transmissivity, specific capacity, or other field-based aquifer productivity data (Thanh et al., 2022; George, 2024).

Existing local studies in Adamawa are valuable but spatially limited. For example, recent investigations have concentrated on Mubi and Mubi North, using selected hydrogeological factors and GIS-based overlay or AHP techniques to identify local groundwater potential zones (Ndatuwong et al., 2024; Adamu et al., 2024). Such localized assessments cannot adequately support groundwater planning across the entire state because results derived from one local geological setting may not be transferable to other areas with different basement structures, sedimentary formations, terrain, rainfall regimes, and recharge conditions.

The present study therefore provides a methodological and spatial-scale advance by integrating multiple groundwater-conditioning factors within a consistent state-wide geospatial and MCDA framework. Rather than producing isolated local maps, it develops a harmonized groundwater potential assessment covering the whole of Adamawa State. This broader approach enables comparison of groundwater prospects across contrasting hydrogeological zones, identification of regional priority areas for exploration, and provision of a strategic spatial database for borehole siting and water-resource planning. Its contribution is therefore both methodological through systematic multi-factor integration and practical, through a state-wide decision-support framework that can guide more targeted field validation and groundwater development

MATERIALS AND METHODS

Adamawa state is significant part (sub-catchment) of the upper Benue River basin located in the North Eastern part of Nigeria. It lies between Latitudes 07° 00' 00" and 11° 00' 00" North of the Equator and Longitudes 11° 15' 00" and 13° 30' 00" East of the Greenwich Meridian (Figure 1).

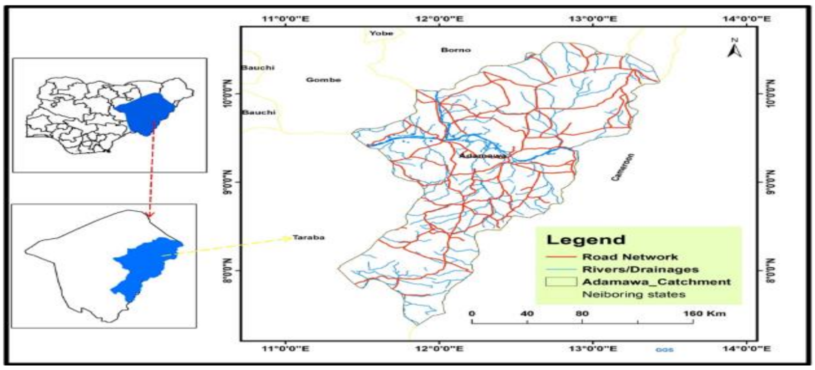

Figure 1: Map of Adamawa state (a sub-catchment of the upper Benue River Basin)

It shares boundary with Taraba State to the south-west, Gombe State to North-west and Borno state to the North. The State has an international boundary with the Republic of Cameroon along its eastern side. It has a land area of about 35,720.96 km^2 (Adebayo, 1997). The state is divided into 21 local government areas. The sub-catchment encompasses the corridor of river Benue flood plain (which is the major river that drains through the sub-catchment) as it traverses through the sub-catchment. For the purpose of this research, data were obtained from various sources. Rainfall data was obtained from Nigerian Meteorological Agency (NIMET) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) through Center for Hydrometeorology and Remote Sensing (CHRS). Satellite images and Digital Elevation Model (DEM) was acquired from the United States Geological Survey (USGS). Table 1, summaries the types of data required for the research, their sources and purposes.

Table 1: Data Types and Sources

S/N	Data types	Source	Resolution	Purpose
1	Sentinel-2 satellite image of 2020	USGS	30m	Land Use/Land Cover Thematic layer
2	SRTM DEM	USGS	10m	Slope/Elevation, Lineament and Drainage Thematic layers
3	Geology Map	Nigerian Geological Survey Agency	1:50,000	Geology thematic layer
4	Soil map	Food and Agricultural Organisation (FAO) World Digital Soil Map		Soil thematic layer
5	Metrological data	NIMET, CHRS, RUWASSA and UBRBDA		Rainfall/Precipitation Thematic layer

The factors influencing groundwater occurrence and distribution (thematic factors) such as: Rainfall, lineament density, drainage density, geology, slope, and soil and land use/land cover were analyzed using ArcGIS 10.8 software. The thematic factors were allocated weights proportional to their level of importance in influencing groundwater occurrence and distribution. A hierarchical ranking was then done based on pairwise comparison matrix of AHP on the parameters so as to obtain their normalized weights. Comparisons were done in pairs based on specific criterion in relation to other criteria and the weight for each parameter (criterion) was then determined. The accuracy of the matrix was estimated by a Consistency Ratio (CR) assessment (Ndhlovu and Woyessa, 2021). The final criteria (sum value) weights of the thematic layers for each of the factors obtained were then reclassified and comparison of individual influencing factor done to see which factor predominates at any chosen location. To produce the GWP map various thematic maps of individual criterion (groundwater influencing factors) were integrated using weighted sum overlay analysis in ArcGIS 10.8 environment. The GWPl Map produced was then reclassified into 5 delineated zones (categories) of very low, low, moderate and high and very high groundwater potential zones.

$$GWPM = RFw + LDw + DDw + GLw + SLw + SOw + LULCw \quad (1)$$

Where;

GWPM = Groundwater Potential Map; RF = Rainfall; LD = Lineament Density; DD = Drainage Density; GL = Geology; SL = Slope; SO = Soil; LULC =Land use/Land cover and
w = the normalized weight of each thematic factor.

The areal extent of each GWPzone (i.e., reclassified zones) was calculated from Groundwater Potential Map (GWPM). The GWPM is in raster format data type and images in raster format data type are made up of pixels which determine the resolution of the image. The counts of the pixels occupied by the potential zones were used to calculate the actual area covered by each zone. The raster calculator tool in ArcGIS 10.8 was employed in calculating the area of each zone in square kilometers using the formula; 2

$$\text{Area (km}^2\text{)} = \frac{\text{(Pixel Count) x Pixel size x Pixel size}}{1{,}000{,}000} \quad (2)$$

In this study stratified and purposive sampling techniques were employed for sampling boreholes. This was done so as to capture data from various locations cutting across wards within L.G.As based on the number of borehole data (obtained from RUWASSA, Ministry of Water Resources, UBRBDA as well as from various contractors/consultancy firms) and their distribution within the sub-catchment. Representative spread of about 414 borehole data cutting across the entire sub-catchment were selected and used for validation of the research work. To assess statistical significance, a t-test was performed using the sample size ($n = 414$). The resulting test statistic is extremely high, yielding a p-value far less than 0.001 ($p < 0.001$). This indicates that the observed correlation is highly statistically significant and unlikely to have occurred by chance. Therefore, the relationship between groundwater potential zones and borehole yields is both strong and statistically reliable.

RESULTS AND DISCUSSION

Factors Influencing Groundwater Potential in Adamawa State

The groundwater potential zones result from the spatial interaction of rainfall, lineament density, drainage density, geology, slope, soil, and land use/land cover. Areas receiving higher rainfall generally have greater groundwater recharge, particularly where permeable soils and favourable geological formations allow infiltration. High lineament density enhances groundwater movement and storage by providing fractures and conduits, while low drainage density often indicates greater infiltration and therefore higher recharge potential. Geology controls the ability of subsurface materials to store and transmit groundwater, with permeable formations producing more favourable conditions. Gentle slopes promote infiltration by slowing surface runoff, whereas steep slopes encourage rapid runoff and reduce recharge. Soil characteristics further influence infiltration, with permeable soils favouring recharge. Land use/land cover modifies surface conditions; vegetated areas can enhance infiltration, while built-up surfaces increase runoff. Consequently, locations where favourable conditions overlap produce very high and high potential zones, whereas areas characterized by low rainfall, impermeable geology, steep slopes, low lineament density, and intensive runoff tend to form low and very low potential zones.

Slope

The slope in Adamawa state (sub-catchment of Upper Benue River Basin) was found to range between 0° to 72.62°. As shown in Figure 2 the southern part of the sub-catchment has the highest value of slope, while the central region up to the northern part has low slope values. As posited by Balakrishnan (2019), slope has an inverse relationship with GWP, high slope causes less penetration due to fast surface runoff while, level and mild slope areas encourage minimum runoff, allowing for additional time to infiltrate rainwater allowing for groundwater rejuvenation. The slope map of Adamawa sub-catchment of the upper Benue River basin was reclassified into low slope (<8°), moderate slope (8-15°) and high slope (>15°) (Figure 3). This classification of slope according to Elewa and Qaddah (2011) corresponds to high potential, moderate potential and low potential of groundwater in an area. Based on the reclassified slope in terms of area, about 35008.72 km^2 of the sub-catchment is characterized by low slope class which represents 98.01% of the total area of the sub-catchment, 687.04 km^2 (1.92%) of the sub-catchment is characterized by moderate slope class and 25.19 km^2 (0.07%) of the sub-catchment is characterized by high slope class. The highest slope areas were found in the southern and the extreme northern part of the sub-catchment. This is similar to the work of Rilwanu (2017) whose findings showed that Southern parts of Kano (Northwestern Nigeria) are higher in terms of slope and elevation.

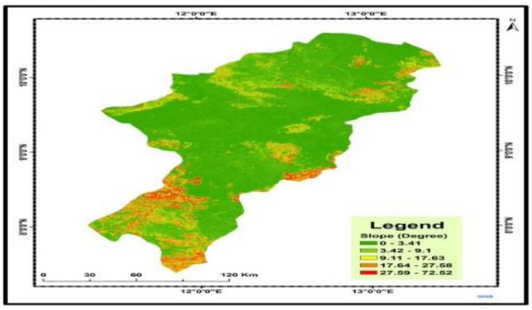

Figure 2: Slope map of the study area

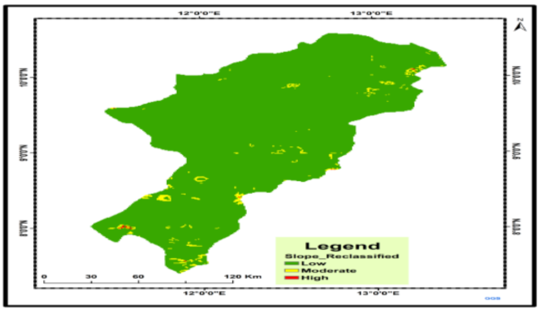

Figure 3: Reclassified Slope of the study area

Geology

The Adamawa state is underlain by Basement Complex and Sedimentary terrain characterized by about 13 geological units namely; Shale, Sandy clay, Calcerous sandstones, Yonger Basalt, Porphyritic Granite/Coarse Porphyritic biotite and hornblende granite, Migmatite, Shale, Limestone, Sandstone, Feldspathic Sandstone/Calcerous Sandstone and Shelly Limestone, Medium to coarse grained Biotite granite, Migmatite Gneiss, Alluvium and Basalt (Figure 4). The Migmatite Gneiss predominates in the state (sub-catchment) accounting for 27.69% of the rock type found in the area, followed by Migmatite (19.55%). Fashae et al. (2014) opined that usually, massive unfractured lithologic units in Basement Complex setting have little influence on groundwater availability except in cases with secondary porosity through the development of weathered overburden and fractured bedrock units, which form potential groundwater zones.

Magaia et al. (2018) and Oladunjoye et al. (2019) highlighted the standard for geology in relation to groundwater potential and how various geological formations affect groundwater potentiality. On this basis, the geology of the sub-catchment was reclassified based on its potentiality for groundwater occurrence as shown in Figure 5 with sedimentary terrain having high potential while basement complex (crystalline rocks) had the low potentiality.

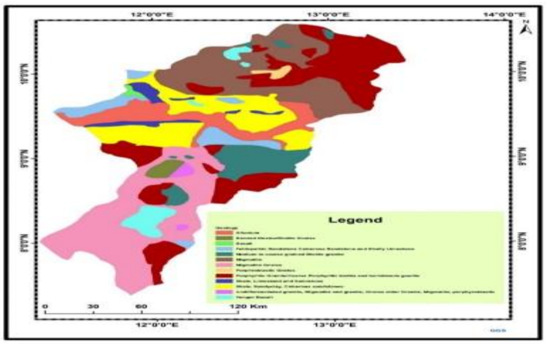

Figure 4: Geology of the study area

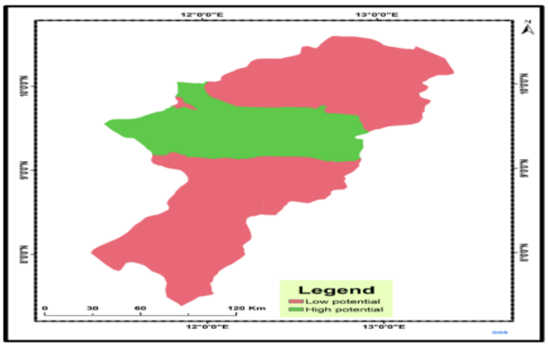

Figure 5: Reclassified Map of Geology

Soil Types

As shown in Figure 6, Adamawa state is covered by about seven soil types namely; Clay, Clay-Loam, Loam, Loamy-Sand, Sand, Sandy-Clay-Loam and Sandy-Loam. Loam soil is the predominant soil type in the state (sub-catchment) covering an area of about 12071.22km^2 which represent 33.79% of the entire land area. The second largest soil type is Sandy-loam covering an area of 7265.45km^2 (20.34%) followed by loamy-sand (11.70%). The reclassification of soil types within the state (sub-catchment) into 3 different classes of groundwater potentiality was based on Amedu et al. (2017) and Abdulazeez and Adamu (2018). Soils with high permeability allow more water to percolate or infiltrate into aquifers, while compacted or clayey soils hinder infiltration, reducing groundwater recharge of aquifers (Figure 7).

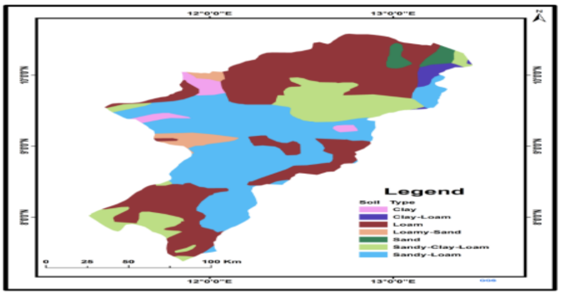

Figure 6: Soil type map

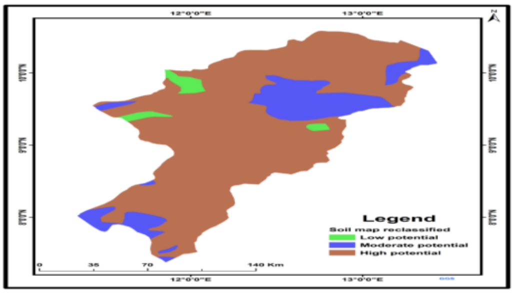

Figure 7: Reclassified soil type map

Rainfall distribution across the Adamawa Sub-catchment

The annual aggregate rainfall values in the state ranges between 1,998.36 mm to 3,238.26 mm (Figure 8). Rainfall is the major source of groundwater recharge thus; it has a great influence on groundwater occurrence especially in basins and sub-catchments. Hence, the Adamawa sub-catchment is not exclusive. According to Midaoui et al. (2024), the groundwater potential of a place is high if the rainfall values are high. Conversely, low if rainfall is values are low. With lowest annual aggregate rainfall value in the catchment being 1,998.36 mm, it can be said that the sub-catchment is potentially viable in terms of groundwater availability and occurrence.

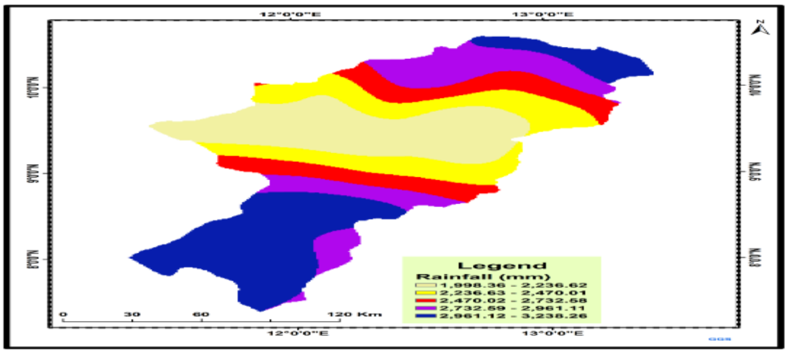

Figure 8: Rainfall map of Adamawa State

Land Use and Land Cover (LULC)

The Land use and Land Cover (LULC) of Adamawa state was classified into six classes (Figure 9) namely; Water bodies occupying 182.41 km^2 which represent 0.51% of the study area, forest 4737.22 km^2 (13.26 %), vegetation 28602.52 km^2 (80.07%), farmlands 1802.18 km^2 (5.05%), built up areas 305.60 km^2 (0.86%) and bare surface 91.03 km^2 (0.25%). According to Siddik et al. (2022), the long-term temporal and seasonal changes in LULC have a substantial influence on groundwater flow dynamics. Each of the classes of LULC in this study has influence on groundwater recharge and occurrence in that area. For instance, the amount of water that infiltrates into the soil to form groundwater depends on the vegetation cover as vegetation impacts the speed of water that will move across a surface (Sun et al. 2017). Similarly, in built up area, man-made features, like pavement usually inhibit infiltration. The land use and land cover distribution in the catchment is presented in Figure 9. It can be seen from the figure that the forested areas are found mainly in the southern part of the sub-catchment while significant water bodies are located in the central region of the sub-catchment. Farming activities are found across the sub-catchment most especially along water bodies to enhance irrigation activities.

The reclassified land use and land cover of the sub-catchment is presented in Figure 10. The reclassification is based on the fact that different LULC have different influences and potential for groundwater occurrence. According to Sun *et al.* (2017), areas covered with water bodies undoubtedly have high groundwater potential while areas covered by vegetation have moderate potentiality.

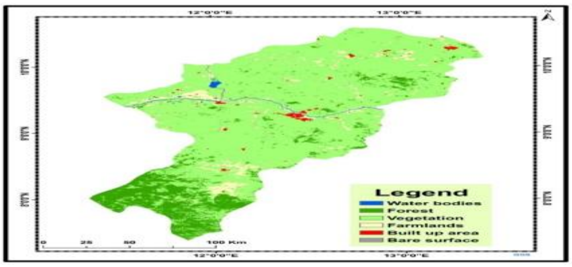

Figure 9: LULC of the study area

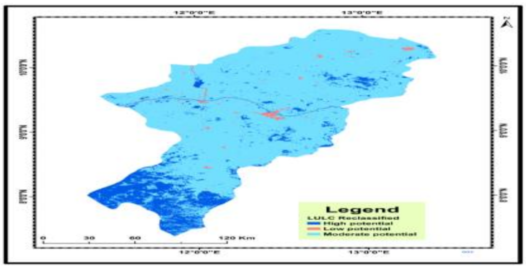

Figure 10: Reclassified LULC of the syudy area

Drainage Density

The drainage density of Adamawa state was found to range between 0 to 34.58 km/km^2. This implies that for every square km travel within the state (sub-catchment) 0 to 34.58km of stream/river is encountered. As shown in figure 11 the central areas of the state have the highest drainage density. The reclassification of drainage density in this study was based on the work of Danso and Ma (2023). The drainage density of the state was reclassified into three namely, low (0-1km/km^2), moderate (1-20 km/km^2) and high (>20 km/km^2) density (Figure 12**)**. A total area of 19725.96 km^2 (55.22% of the total area of the state) is characterized by low drainage density, 12673.09 km^2 (35.48%) characterized by moderate drainage density and 3321.89 km^2 (9.30%) characterized by high drainage density. High drainage density is more prominent central and southern parts of the area.

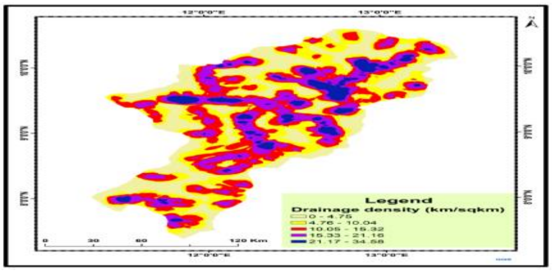

Figure 11: The drainage density map

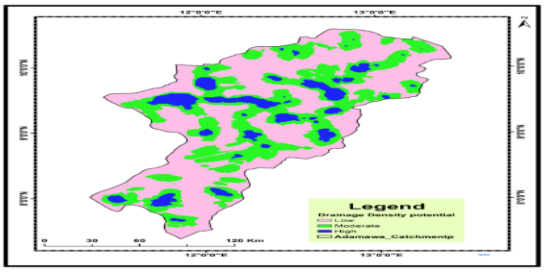

Figure 12: Reclassified drainage density map

Lineament Density

According to Adaviruku et al. (2023), in a basement complex the presence of lineaments and its density is a major determinant of groundwater recharge and occurrence. A total number of 365 lineaments were extracted from the Digital Elevation Model (DEM) with a total length of 2,927.23km. This figure is a little bit at variance with that of Adaviruku and Oyatayo (2023) probably due to incorporation of 250:55 Azimuth and Altitude ratio that enhanced minor lineament extraction in this research study. The result of the lineament extraction is presented as a lineament map in Figure 13. Lineaments were observed to be more concentrated in the northern and southern parts of the study area (state) while the central region has sparse lineament. This is due to the fact that the central region of the state (sub-catchment) is overlain by sedimentary rocks of Upper Cretaceous to Quaternary.

Reclassification of lineament density was based on Rajasekhar et al. (2021). The lineament density of the study area (state/sub-catchment) is as shown in Figure 14. The reclassified lineament density was categorized into three; (0-1 km/km^2), (1-2 km/km^2) and (>2 km/km^2) representing lineament density with groundwater occurrence potentiality of low, moderate and high respectively. It was observed from the result that about 216.32km^2 which represent 66.16% of the study area was characterized by low lineament, 96.85 km^2 (29.62%) was moderate and 13.78 km^2 representing 4.22% was high. The denser lineament signified the intensity of rock fracturing, which is a prerequisite for development of conduits for groundwater in basement complex. The northern and southern parts of the sub-catchment have more lineament density implying that groundwater have more potentiality in these areas than other areas within the context of the study area.

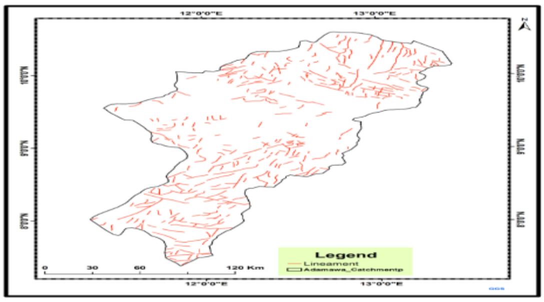

Figure 13: Lineament map

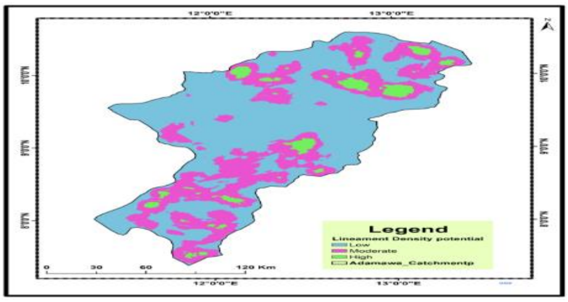

Figure 14: Reclassified Lineament Density map

Pairwise Comparison of the Different Groundwater Influencing Factors

As shown in Table 2 the pairwise comparison of the different groundwater influencing factors (thematic factors) considered shows that geology had the highest (24.6%) influence on groundwater occurrence in the sub-catchment followed by rainfall (20.8%) and drainage density weighted (17.0%). Soil, lineament, slope, and land use/land cover weighted 13.7%, 11.2%, 8.4% and 4.4% respectively. This is in contrast to the work of Amedu *et al.* (2017) which found that rainfall and lineament had 33% and 28% influence on groundwater potential in Omala, located within the Lower Niger River basin in North central Nigeria.

The pairwise comparison as shown in Table 2 has a consistency ratio of 0.06 implying high level of consistency in the weighting of the various factor integrated to produce the final groundwater potential zone map.

Table 2: Pairwise Comparison and Weighting of Groundwater Influencing Factors

	Rainfall	**Lineament**	**Drainage density**	**Slope**	**LULC**	**Geology**	**Soil**	**Rank**	**Weight**	**Ranking**
Rainfall	1	2	1	2	3	1	3	6	20.8%	2
Lineament	1/2	1	1	2	3	1/3	½	3	11.2%	5
Drainage density	1	1	1	2	5	1/2	2	5	17.0%	3
Slope	1/2	1/2	1/2	1	3	1/2	1/3	2	8.4%	6
LULC	1/3	1/3	1/5	1/3	1	1/3	1/4	1	4.4%	7
Geology	1	3	2	2	3	1	3	7	24.6%	1

	Rainfall	Lineament	Drainage density	Slope	LULC	Geology	Soil	Rank	Weight	Ranking
Soil	1/3	2	1/2	3	4	1/3	1	4	13.7%	4

CR = 0.06

Groundwater Potential Map of Adamawa State

The groundwater potential map produced is as shown in figure 15. The produced map was reclassified into 5 zones of very low, low, moderate and high and very high groundwater potential zones as shown in Figure 16. The areas with very high groundwater potential are mainly found in the central and parts of southern region of the sub-catchment. This aligns with the fact that the central region of the state is associated with or underlain by sedimentary formation; furthermore, it has soil of high porosity, high drainage density in addition to receiving high rainfall and low slope in this part. This is in agreement with the work of Amedu et al. (2017) which found that the high groundwater potential zone in Omala (located within the Lower Niger River basin in Kogi state North central Nigeria) was predominantly in the part of the sub-catchment that received the highest amount of rainfall. The high potential and moderate potential are found across the whole of the catchment, this implies that in overall the Adamawa sub-catchment of the upper Benue River Basin has a fairly good spread in terms of potentiality for groundwater resources. This result is similar to the work of Gidado and Abdulkadir (2018) which observed that each of groundwater potential zone cuts across many parts of Ilorin Metropolitan Area (located within the Lower Niger River basin north central Nigeria).

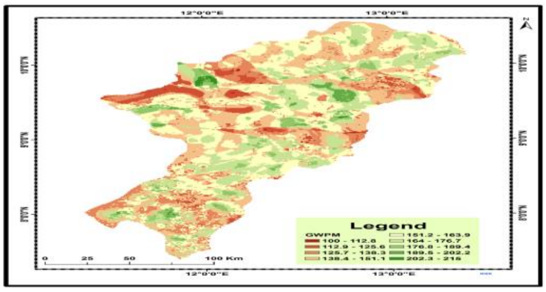

Figure 15: Groundwater Potential Adamawa Sub-catchment

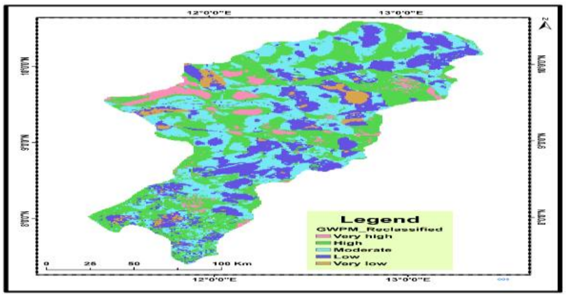

Figure 16: Reclassified Groundwater Potential Adamawa State

Table 3: Areal Coverage of Groundwater Potential Zones in the State

Potentiality	Area (Sq km)	%
Very high	1811.00	5.07
High	11364.66	31.82
Moderate	8153.76	22.83
Low	13332.71	37.32
Very low	1058.84	2.96
	35720.96	100

As presented in Table 3 very low potential zones cover an area of 1058.84 km^2 which represent mere 2.96% of the sub-catchment; low potential zone covers an area of 13332.71 representing 37.32%, moderate potential zone covers an area of 8153.76 km^2 representing 22.83%, high potential zone covers 11364.66 km^2 representing 31.82% and very high potential zones covered an area of 1811 km^2 representing 5.07% of the sub-catchment. The very high potential is mostly found within the central region and parts of the southern region of the sub-catchment. From table 3 it can be inferred that the percentage in terms of potentiality ranging from moderate to very high accounts for about 59.78% of the total area of the sub-catchment which implies that larger part of the sub-catchment is viable for groundwater development.

Validation of groundwater potential map with borehole yields

The relationship between the GWPZ values and the yields of the existing boreholes was determined by Pearson correlation analysis. The geographic coordinates of all the boreholes were inputted into ArcGIS environment and overlaid on the GWPZ as shown in Figure 17. Having overlaid the coordinates on the GWPZ, it was found that 78.20% of the boreholes fell on areas corresponding to their yields. This finding is closely in alignment with that of Adaviruku *et al.* (2023), which found that 81.25% of the boreholes in Okene L.G.A (located in the Lower Niger River Basin) had yields that corresponded to their groundwater potential zones. Furthermore, the result from the finding of this research was found to be closely in agreement to the findings of a similar work done by Danso and Ma (2023) and Abrar *et al*. (2021) which established that about 76.5% and 79.2% of the boreholes fell within suitable sites for groundwater discovery in coastal municipality of Ghana and in the Western escarpment of the Ethiopian Rift valley respectively.

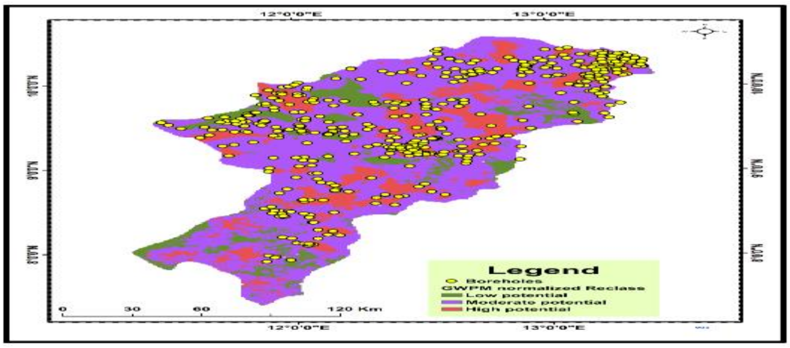

Figure 17: Borehole Points Overlaid on GWPZs Map in the Sub-catchment

The result of Pearson moment correlation analysis is shown in Table 2. As shown in the Table 2, R is positive (+) 0.782. It is imperative to note that the value of R is meant to show the direction and strength of the relationship between the yields of existing boreholes in the sub-catchment and the groundwater potential map produced. The relationship is a positive, meaning that as groundwater potential increases as borehole yield increases correspondingly. The strength of the relation is strong (R = 0.782).

The coefficient of determination (R^2) is obtained by squaring the correlation coefficient, giving $R^2 = 0.782^2 \approx 0.612$. This implies that approximately 61.2% of the variation in borehole yields can be explained by the spatial variation in groundwater potential zones, while the remaining 38.8% may be attributed to other factors such as local hydrogeological conditions, drilling depth, or aquifer characteristics. The resulting test statistic is extremely high, yielding a p-value far less than 0.001 ($p < 0.001$). This indicates that the observed correlation is highly statistically significant and unlikely to have occurred by chance. Therefore, the relationship between groundwater potential zones and borehole yields is both strong and statistically reliable.

Table 2: Correlation Table

	GWPMV values	Borehole Yields
GWPMV values	1	
Borehole Yields	0.78204	1

($p < 0.001$, $R^2 \approx 0.612$)

The results of this study demonstrate a strong spatial agreement between groundwater potential zones and observed borehole yields in the Adamawa sub-catchment of the Upper Benue River Basin. The finding that 78.20% of boreholes fall within zones corresponding to their actual yields, together with a Pearson correlation coefficient (R = 0.782), provides compelling evidence that the groundwater potential mapping approach used in this study is reasonably reliable.

A Pearson correlation coefficient of 0.782 indicates a strong positive relationship between predicted groundwater potential and observed borehole yields. In practical terms, this means that areas classified as high groundwater potential tend to produce higher borehole yields, while low-potential zones generally correspond to lower yields. Within the context of similar African studies, correlation values in the range of 0.6–0.8 are often considered good validation outcomes for GIS-based groundwater potential models, especially in data-scarce environments. Many studies across Nigeria, Ghana, and Ethiopia report comparable validation strengths, reflecting the inherent complexity of subsurface hydrogeological systems. Therefore, the value obtained in this study suggests that the integration of thematic layers (such as geology, slope, drainage density, and lineament density) and the applied weighting scheme have effectively captured the dominant controls on groundwater occurrence in the study area (Danso and Ma, 2023; Abrar et al. 2021).

CONCLUSION

This study has shown the effectiveness of integrating GIS, remote sensing, and Multi-Criteria Decision Analysis (based on AHP) techniques in GWP assessment within Adamawa state which is a major sub-catchment of the Upper Benue River Basin Northeastern Nigeria. The findings revealed that geology, rainfall, and drainage density are the major factors influencing groundwater occurrence and distribution in the area. The generated groundwater potential zonation map showed that over half of the sub-catchment possesses moderate to very high groundwater potential, indicating favorable viability for sustainable groundwater development, planning, and resource management within Adamawa state. The groundwater potential zones map produced revealed that very low potential zones cover an area of 1058.84 km^2 which represent mere 2.96% of the sub-catchment; low potential zone covers an area of 13332.71 km^2 representing 37.32%, moderate potential zone covers an area of 8153.76 km^2 representing 22.83%, high potential zone covers 11364.66 km2 representing 31.82% and very high potential zones covered an area of 1811 km^2 representing 5.07% of the sub-catchment. The very high potential is mostly found within the central region and parts of the southern region of the sub-catchment. It can be inferred that the percentage in terms of potentiality ranging from moderate to very high accounts for about 59.78% of the total area of the sub-catchment which implies that larger part of the sub-catchment is viable for groundwater development. The result of Pearson moment correlation between groundwater potential map produced and the existing borehole yield in the area shown a positive (+) 0.782 correlation. It is imperative to note that the value of R is meant to show the direction and strength of the relationship between the yields of existing boreholes in the sub-catchment and the groundwater potential map produced. The relationship is a positive, meaning that as groundwater potential increases the borehole yield increases correspondingly. The strength of the relation is strong (R = 0.782).

Recommendation

Based on the findings of this study, the following recommendations are proposed

i. Establishment of groundwater monitoring units across the state (sub-catchment) for periodic evaluation of groundwater yield to enhance data collection for the purpose of groundwater prospecting.

ii. Adoption of simple but effective and sustainable groundwater management strategies such as afforestation and soil conservation practices should be encouraged on bare land sloppy land terrains so as to mitigate high rainfall runoff which negatively impacts groundwater potentiality (availability) in such areas within the sub-catchment (state).

iii. In areas of very low groundwater potentiality as well as areas where there is anticipated increase in population (based on population growth projection) it is important to estimate projected water demand of those locations vis-à-vis groundwater potential (in terms of aquifer productive yield) of those locations so as to check indiscriminate drilling of boreholes which could result in groundwater 'stress condition' and increased of incidences of borehole failure. This measure will avail regulatory agencies the opportunity to formulate and enact appropriate legislation that will check such unsustainable borehole development practices.

REFERENCES

Abdulazeez, A. and Adamu G. K. N. (2018). An appraisal of factors affecting groundwater formation and recharge in parts of Northern Kano State, Nigeria. The Nigeria Association of Hydrological Sciences 9th International Conference, Edo 2018.

Adamu, B. G., Umar, M., Zakari, D. M. and Babale, D. B. (2024). Determination of groundwater potential areas using remote sensing (RS) and GIS techniques in Mubi North Local Government Area, Adamawa State, North Eastern Nigeria. International Journal of Research and Innovation in Social Science, 8(4), 1545–1556.

Adaviruku, P. E., Akpu, B., Zubairu, S. M. and Oyatayo, K. T. (2024). Geospatial analysis of groundwater potential zones in Okene Local Government Area, Kogi State, Nigeria. *The Nigerian Geographical Journal*, 18(2), 39–48.

Adaviruku, P. E. and Oyatayo, K. T. (2023). Extraction, mapping, and analysis of structural lineaments using geospatial Azimuth-Altitude ratio technique on a DEM of a sub-catchment of the Upper Benue River Basin, Nigeria. *European Journal of Theoretical and Applied Sciences*, 1(6), 1–5. https://doi.org/10.59324/ejtas.2023.1(6).90

Adebayo, A. A. (1997). The Agroclimatology of rice production in Adamawa State Ph.D Thesis Dept of Geography F.U.T. Minna, Nigeria. Pp 78.

Alrawi, I., Chen, J. and Othman, A. A. (2022). Groundwater Potential Zone Mapping: Integration of Multi-Criteria Decision Analysis (MCDA) and GIS Techniques for the Al-Qalamoun Region in Syria. *ISPRS International Journal of Geo-Information*, 11(12), 603. https://doi.org/10.3390/ijgi11120603

Amedu, M. A., Akpu, A. and Musa, I. J. (2017). Geospatial analysis of groundwater potential zones in Omala Local Government Area, Kogi State, Nigeria. *Dutse Journal of Pure and Applied Sciences (DUJOPAS)*, 3(2):227-238.

Amos-Uhegbu, C., Jokotagba, S. T., Aigba, P. I., Dinneya, O. C., & Akoma, C. D. (2024). Delineation of the groundwater potential zones using integrated geospatial techniques and multi-criteria decision approach in the Cretaceous Lower Benue and Niger Delta Basins of Abia State, Southern Nigeria. *Nigerian Journal of Physics*, 33(S), 23–43.

Aranguren-Díaz, Y., Galán-Freyle, N. J., Guerra, A., Manares-Romero, A., Pacheco-Londoño, L. C., Romero-Coronado, A., Vidal-Figueroa, N. and Machado-Sierra, E. (2024). Aquifers and Groundwater: Challenges and Opportunities in Water Resource Management in Colombia. *Water*, 16(5), 685. https://doi.org/10.3390/w16050685

Balakrishnan, M. (2019). Groundwater Potential Zone Mapping using Geospatial Techniques in Walayar Watershed. *International Journal of Engineering and Advanced Technology - (IJEAT,)* 9 (1) 1157-1161. https://doi.org/10.35940/ijeat.A9511.109119

Danert, K. and Healy, A. (2021). Monitoring Groundwater Use as a Domestic Water Source by Urban Households: Analysis of Data from Lagos State, Nigeria and Sub-Saharan Africa with Implications for Policy and Practice. *Water*, 13(4), 568. https://doi.org/10.3390/w13040568

Danso, S. Y. and Ma, Y. (2023). Geospatial techniques for groundwater potential zones delineation in a coastal municipality, Ghana. *The Egyptian Journal of Remote Sensing and Space Sciences* 26: 75–84. https://doi.org/10.1016/j.ejrs.2022.12.004

George, B. (2024). Analysis of methods used to validate remote sensing and GIS-based groundwater potential maps in the last two decades: A review. *Geosystems and Geoenvironment*, 3(1), https://doi.org/10.1016/j.geogeo.2023.100245

Echogdali, F. Z., Boutaleb, S., Bendarma, A., Saidi, M. E., Aadraoui, M., Abioui, M., Ouchchen, M., Abdelrahman, K., Fnais, M. S. and Sajinkumar, K. S. (2022). Application of Analytical Hierarchy Process and Geophysical Method for Groundwater Potential Mapping in the Tata Basin, Morocco. *Water*, 14(15), 2393. https://doi.org/10.3390/w14152393

Ejepu, J. S. (2020). Regional assessment of groundwater potential zone using remote sensing, GIS and multi-criteria decision analysis techniques. *Nigerian Annals of Pure and Applied Sciences*, 3(3b), 99–111.

Eludoyin, A. O. and Olanrewaju, O. E. (2022). Water Supply and Quality inthe Sub-Saharan Africa. In book: Clean Water and Sanitation (pp.897-913). https://doi.org/10.1007/978-3-319-95846-0_166

Gidado, Y. H. and Abdulkadir, A. (2018). Delineation of groundwater potential zones in Ilorin Metropolis, Kwara State, Nigeria. *International Journal of Environmental Design and Construction Management*, 18(4)

Igimoh, J. J. O., Modeme, S. C., Tijani, A. and Makata, N. E. (2026). Recurring Water Scarcity in Nigeria: Implications for Domestic Water Access, Public Health, and Sustainable

Management. *Journal of Health, Wellness & Safety Research*, 11(3): 43-60 https://doi.org/10.70382/hujhwsr.v11i3.035

Fashae, O. A., Tijani, M. N., Talabi, A. O. and Adedeji, O. I. (2014). Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: An integrated GIS and remote sensing approach. *Applied Water Science*. 4, 19–38.

Irene, J., Irene, B. N. and Daniels, C. (2025). Not a Drop to Drink: Addressing Nigeria's Deepening Freshwater Crisis. *Water*, 17(12), 1731. https://doi.org/10.3390/w17121731

Jac, V. D. G. (2021). Groundwater resources sustainability. In book: Global Groundwater (pp.331-345). https://doi.org/10.1016/B978-0-12-818172-0.00024-4

Joshua, M. M., Oruonye, E. D., Zemba, A. A. and Yusuf, M. B. (2023). Dynamics of Groundwater Resources of Upper Benue River Basin, Nigeria. *Global Research in Environment and Sustainability*, 1(2): 17-34.

Magaia, L. A., Goto, T., Masoud, A. A. and Koike, K. (2018). Identifying groundwater potential in crystalline basement rocks using remote sensing and electromagnetic sounding techniques in Central Western Mozambique. *Natural Resources Research*, 27:275–298.

Mbah, C. K. and Nur, A. (2022). Geo-Electrical Study for Groundwater Potential of Gude and Environs, Adamawa State, Nigeria. *European Journal of Environment and Earth Sciences*, 3(2):24-30 https://doi.org/10.24018/ejgeo.2022.3.2.245

Midaoui, A., el-hamdouny, M., Elaloui, A., Karroum, M., Boudhar, A. and Lahrach, A. (2024). Groundwater Potential Assessment in the Upper Oum Er-Rbia Basin, Northern Morocco. *Ecological Engineering and Environmental Technology*. 25(6) 27-42. https://doi.org/10.12912/27197050/186547

Ndatuwong, L. G., Ezekiel, K. and Peter, Y. (2024). An integrated approach of remote sensing and GIS for mapping groundwater resources in Mubi Region of Adamawa State, Nigeria. *Advances in Geomatics*, 2(1), 1–16.

Ndhlovu, G.Z. and Woyessa, Y.E. (2021). Integrated Assessment of Groundwater Potential Using Geospatial Techniques in Southern Africa: A Case Study in the Zambezi River Basin. *Water* 13, 2610. https://doi.org/10.3390/w13192610

Odoh, B. I., Ahaneku, C. V., Madu, F. M., Muogbo, C. D., Anozie, H. C., Arukwe-Moses, C. P. and Eze, I. E. (2024). Groundwater Exploration and Management using Geophysical and Remote Sensing Techniques: a Review. *International Journal of Science and Management Studies (IJSMS)*, 7(4):230-243, https://doi.org/10.51386/25815946/ijsms-v7i4p128

Oladunjoye, M. A., Adefehinti, A. and Ganiyu, K. A. O. (2019). Geophysical appraisal of groundwater potential in the crystalline rock of Kishi area, Southwestern Nigeria. *Journal of African Earth Sciences*, 151:107-120

Oniku, A. S., Sunu, S. A., Nur, A., Timtere, P., & Kenda, L. P. (2025). Integrated GIS Technique and Electrical Resistivity Sounding (ERS) for Groundwater Prospecting in Yola Catchment Area, Northern Upper Benue Trough, Nigeria. *Nigerian Journal of Physics*, 34(2), 108-123. https://doi.org/10.62292/10.62292/njp.v34i2.2025.376

Rajasekhar, M., Ajaykumar, K., Sudarsana, R. G. and Bhagat, V. (2021). Identification of artificial groundwater recharge zones in semi-arid region of southern India using geospatial and integrated decision-making approaches. *Environmental Challenges*, 8:100549.

Rilwanu, T. Y. (2017). Impacts of surface topography on groundwater potential in parts of Kano State, Nigeria. *Dutse Journal of Pure and Applied Sciences (DUJOPAS)*, 3(2): 170-183.

Saidu, A. A., Aldrees, A., Dan'azumi, S., Abba, S. I., & Hamza, S. M. (2024). Groundwater potential mapping in semi-arid region of Northern Nigeria by integrating analytic hierarchy process and GIS. *Frontiers in Water*, 6.

Siddik, M. S., Tulip, S., Rahman, A., Islam, M., Torabi, H. A. and Mustafa, S. (2022). The impact of land use and land cover change on groundwater recharge in northwestern Bangladesh. *Journal of Environmental Management*. 315(1).

Singh, S., Shankar, V. and Tripura, J. (2026). Integrated GIS framework for groundwater potential zoning in hilly terrain: remote sensing, field validation, and zonal delineation. *Water Practice and Technology*, 21 (1): 58–71. https://doi.org/10.2166/wpt.2026.191

Shinggu, J. J., Audu, J. and Babale, D. B. (2025). Assessment of groundwater potential for sustainable urban management in Mubi South Local Government Area, Adamawa State Nigeria: A remote sensing and GIS approach. *International Journal of Research and Innovation in Social Science*, IX(III), https://doi.org/10.47772/IJRISS

Sun L., Lizhe Y., Lu H., Di F., Kailun J. and Xiaolin H. (2017). Hydrological Effects of Vegetation Cover Degradation and Environmental Implications in a Semiarid Temperate Steppe, China. *Sustainability* 9, 281

Thanh, N. N., Thunyawatcharakul, P., Ngu, N. H. and Chotpantarat, S. (2022). Global review of groundwater potential models in the last decade: Parameters, model techniques, and validation. *Journal of Hydrology*, 614(2):128501, https://doi.org/10.1016/j.jhydrol.2022.128501

Umar, H., Akinyemi, F., & Oladipo, A. (2024). A triangulation approach for groundwater potential evaluation using geospatial technology and multi-criteria decision analysis (MCDA) in Edo State, Nigeria. *Journal of African Earth Sciences*, 209, 105101.